
Explore the QCD phase structure with elliptic flow in relativistic heavy ion collisions at STAR

Shusu Shi

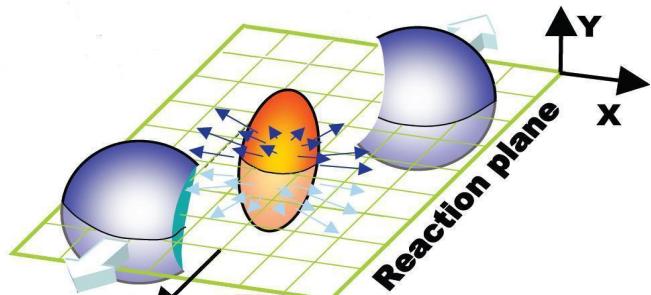
Central China Normal University

Many thanks to: Hiroshi Masui, Md. Nasim and Alex Schmah

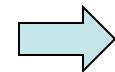
Outline

- **Introduction**
- **Analysis Method**
 - Particle identification
 - v_2 method
- **Results and Discussions**
 - Top Energy Collisions
 - Partonic collectivity
 - Comparison to the viscous hydro
 - Beam Energy Scan
 - Search for the QCD phase boundary
- **Summary and Outlook**

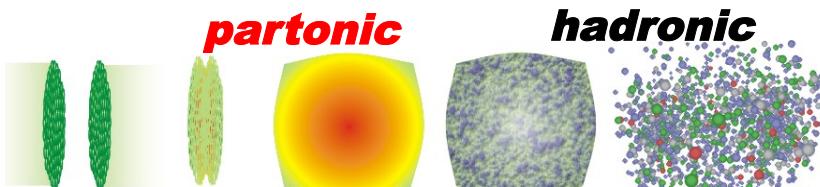
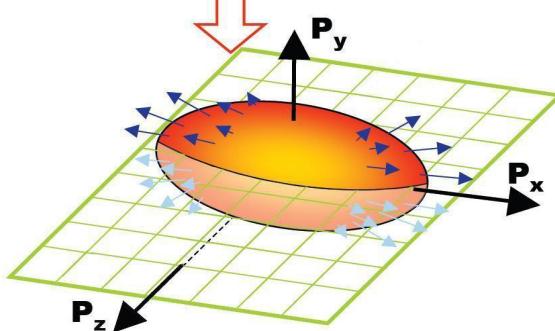
Elliptic Flow (v_2)



$$\varepsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >}$$



$$v_2 = <\cos 2\varphi>, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

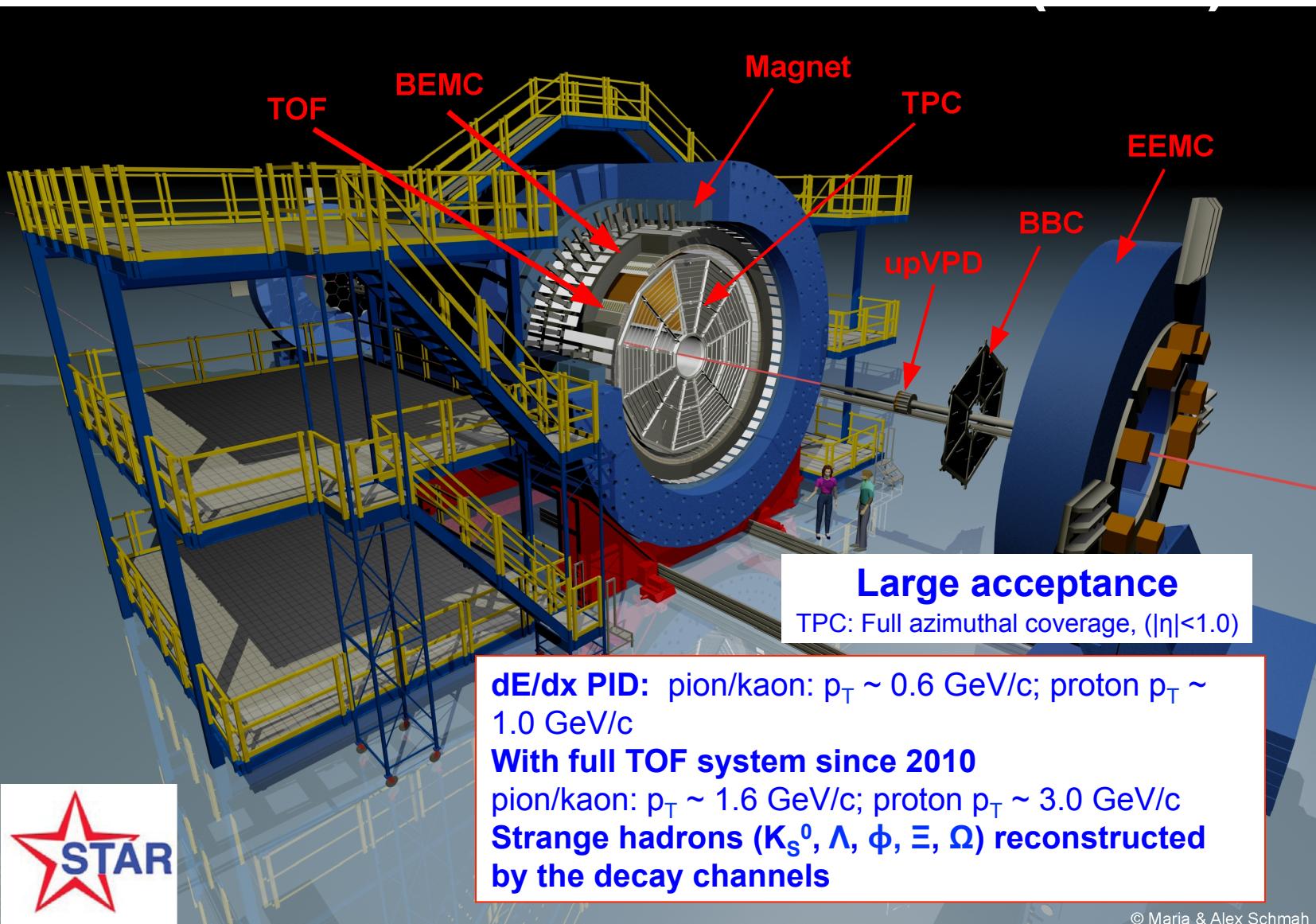


D $\phi, \Omega, \Xi, \Lambda$ π, K, p

- **Elliptic flow** =>
- Initial spatial anisotropy (eccentricity ε)
->final momentum anisotropy v_2
 - ➔ Interactions among constituents
 - Sensitive to degree of thermalization
- Self-quenching with time
 - Sensitive to the early stages of the system evolution
- **Strange hadron => less sensitive to late hadronic rescattering**

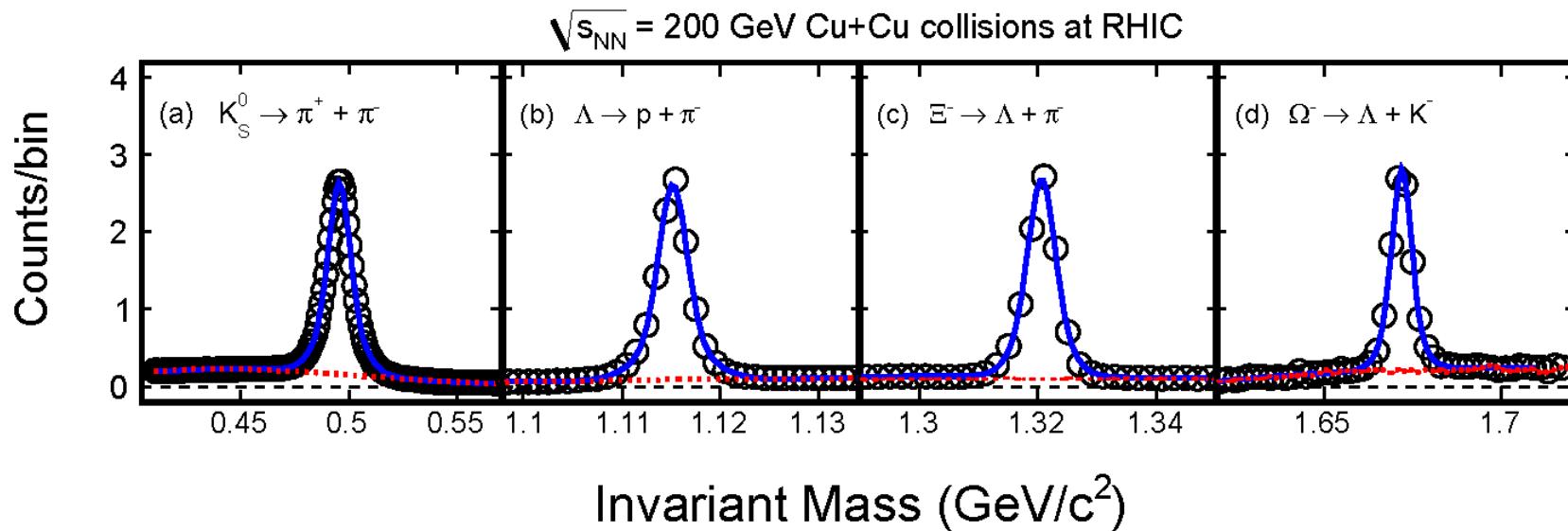
Good probe of the early stage of the collision.

STAR Detectors



© Maria & Alex Schmah

Particle Identification



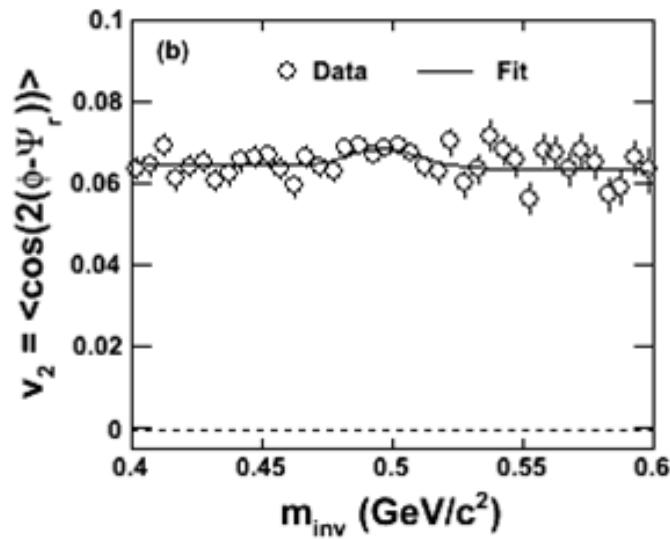
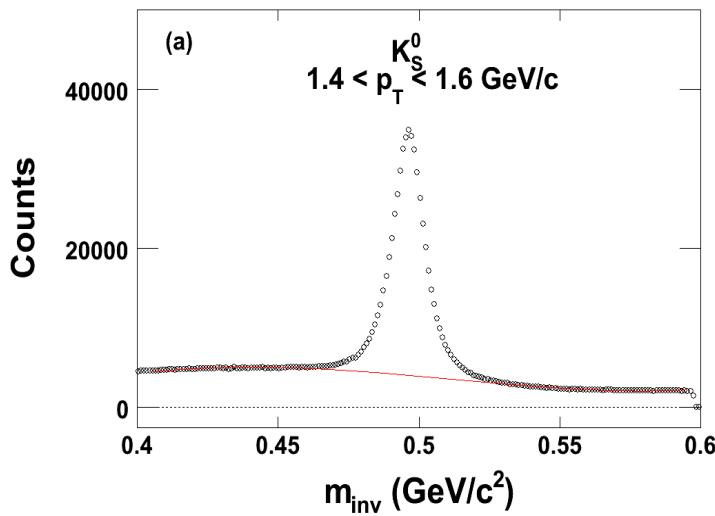
- ✓ Reconstructed by decay topology
 - Daughter hadrons are identified by dE/dx in TPC.
- ✓ Signal to background ratio
 - Depends on colliding system, particle type and p_T .

v_2 Methods

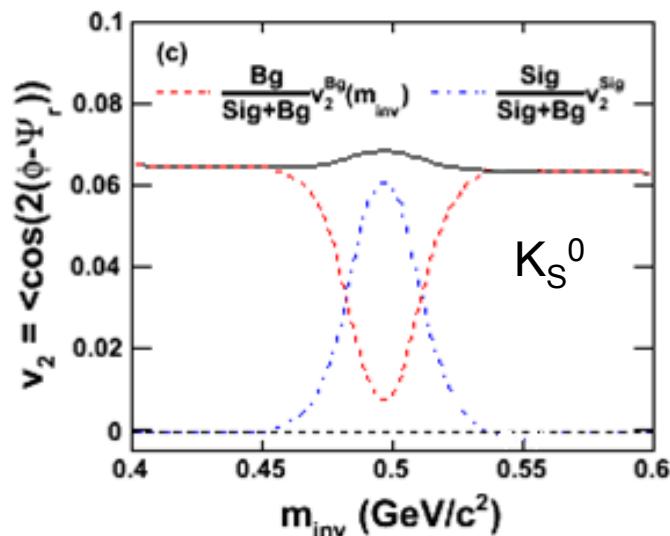
- Two-particle:
 - $v_2\{2\}$: each particle with every other particle
 - $v_2\{\text{EP}\}$ “standard”: each particle with the EP of all the others
 - $v_2\{\text{subEP}\}$: each particle with the EP of the other subevent
- Many-particle:
 - $v_2\{4\}$: 4-particle - 2 * (2-particle)²
 - $v_2\{\text{LYZ}\}$: Lee-Yang Zeros multi-particle correlation
- Different sensitivities to nonflow and fluctuations

Review of azimuthal anisotropy: arXiv: 0809.2949

v_2 versus m_{inv} Method



$$v_2^{Sig+Bg}(m_{inv}) = \langle \cos(2(\phi - \Psi_r)) \rangle = \\ v_2^{Sig} \cdot \frac{Sig}{Sig + Bg}(m_{inv}) + v_2^{Bg}(m_{inv}) \cdot \frac{Bg}{Sig + Bg}(m_{inv})$$

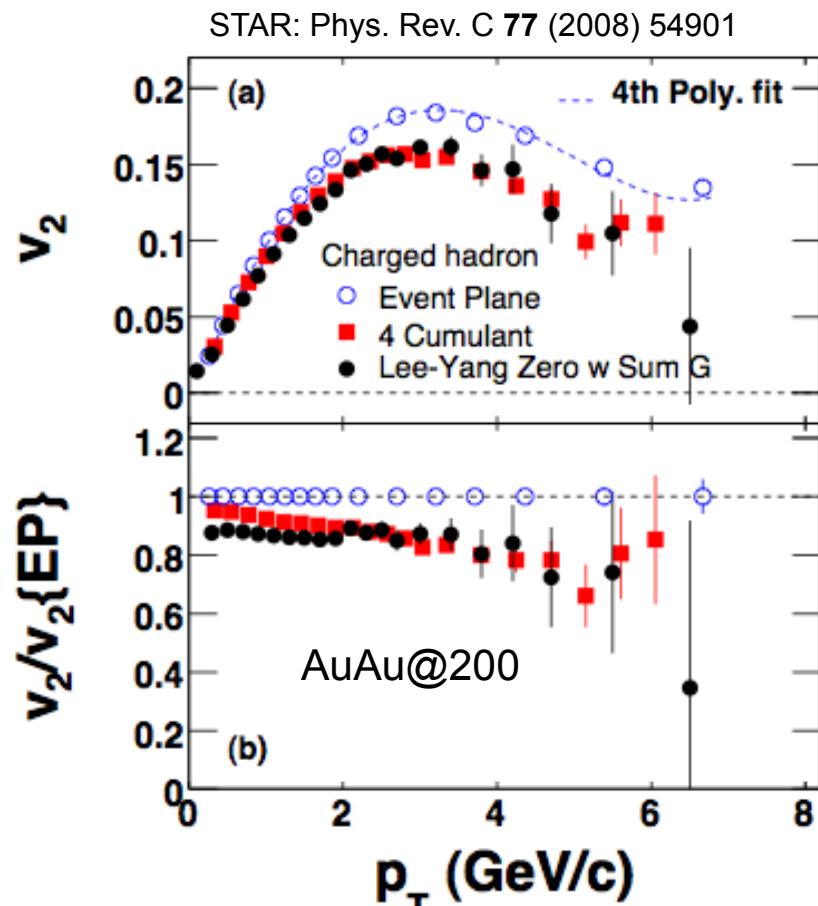
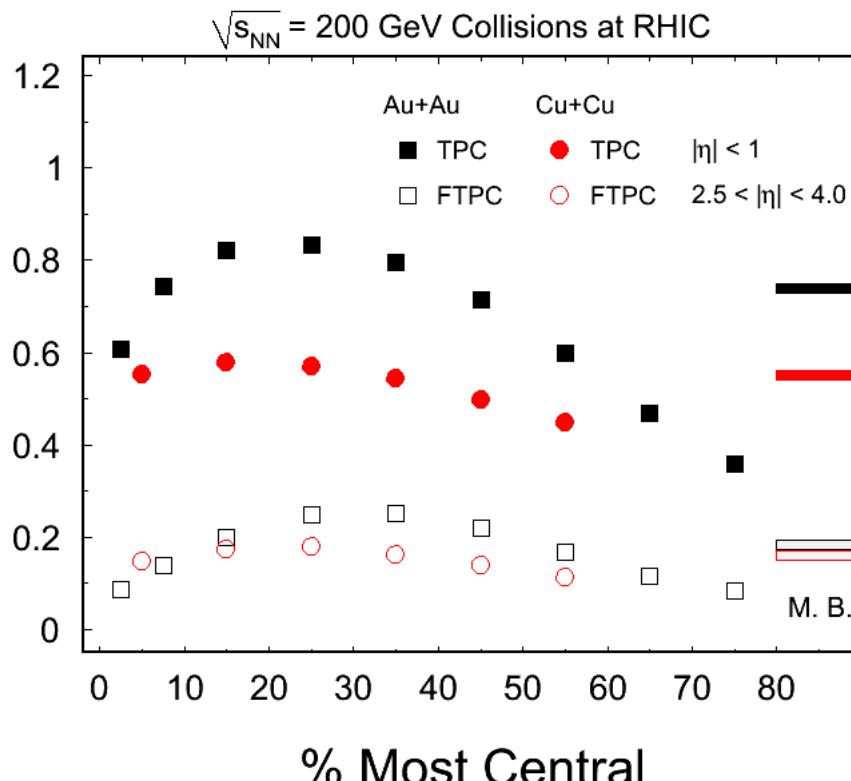


Assume $v_2^{Bg}(m_{inv}) = f(m_{inv})$

Borghini et al. Phys. Rev. C70 (2006)4905

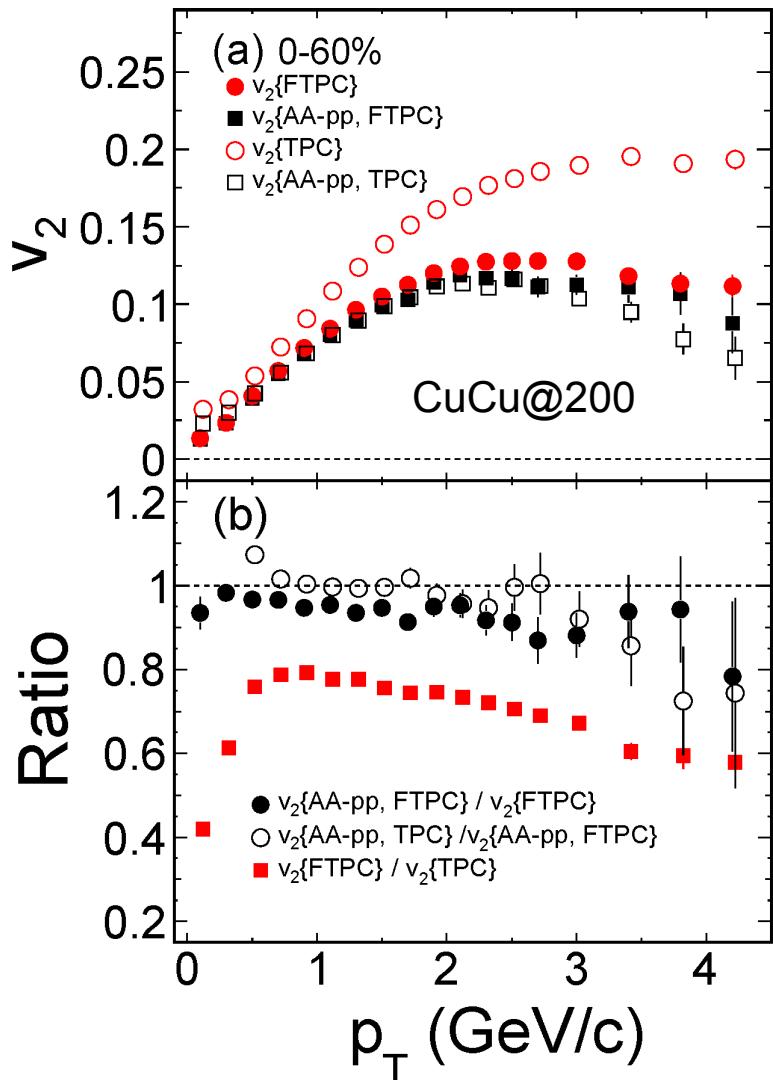
Systematic Study of v_2

Event Plane Resolution



- Large rapidity gap: reduce non-flow contribution
- Non-flow contribution at large p_T region

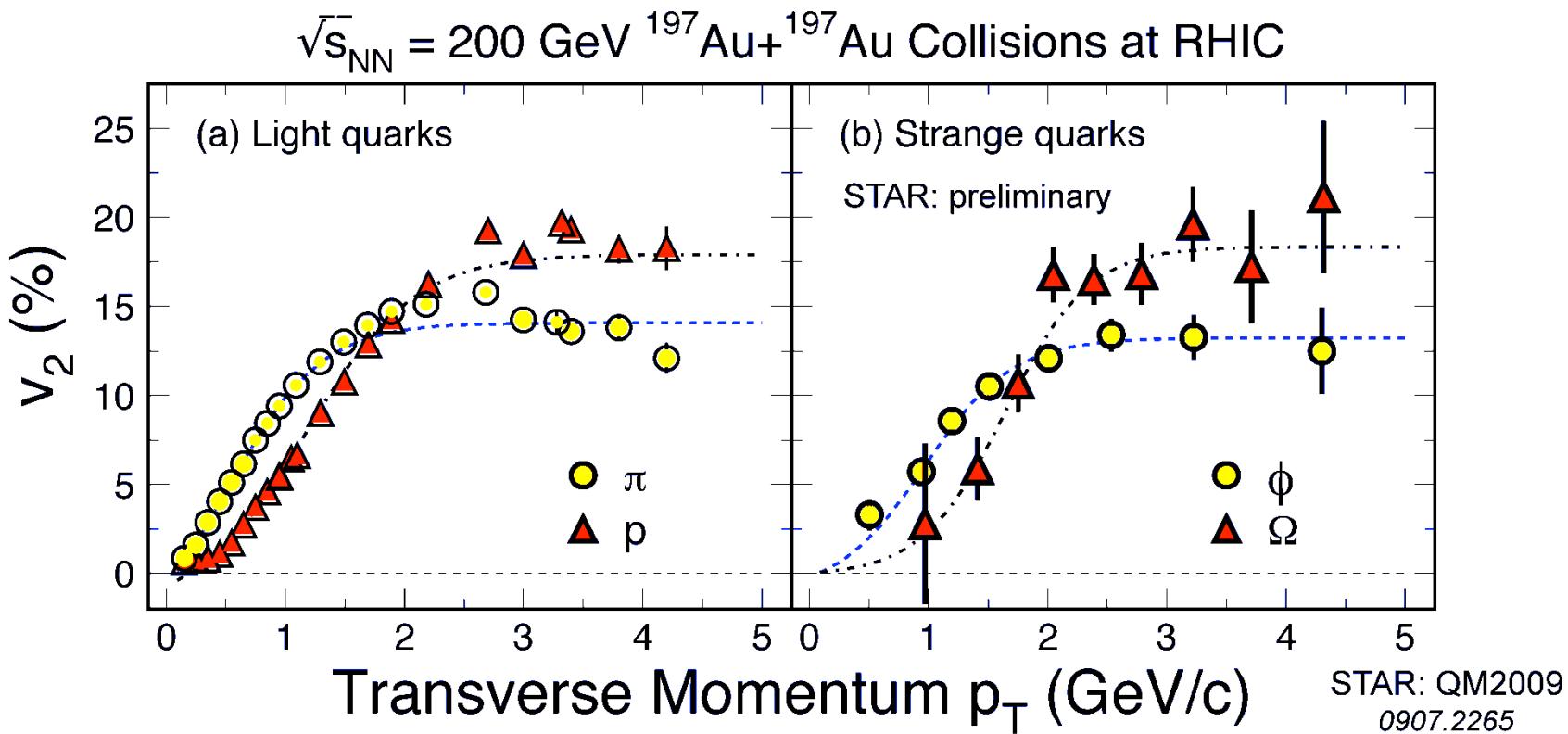
Non-flow in Cu+Cu Collisions



- The eta gap between FTPCs and TPC can reduces most of the non-flow
- $v_2\{\text{AA-pp}\}$: subtract non-flow based on azimuthal correlations in p+p collisions
- Nonflow scales as 1/Multiplicity [1]
- The remaining non-flow $\sim 5\%$

STAR: PRC81, 044902 (2010)
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998).

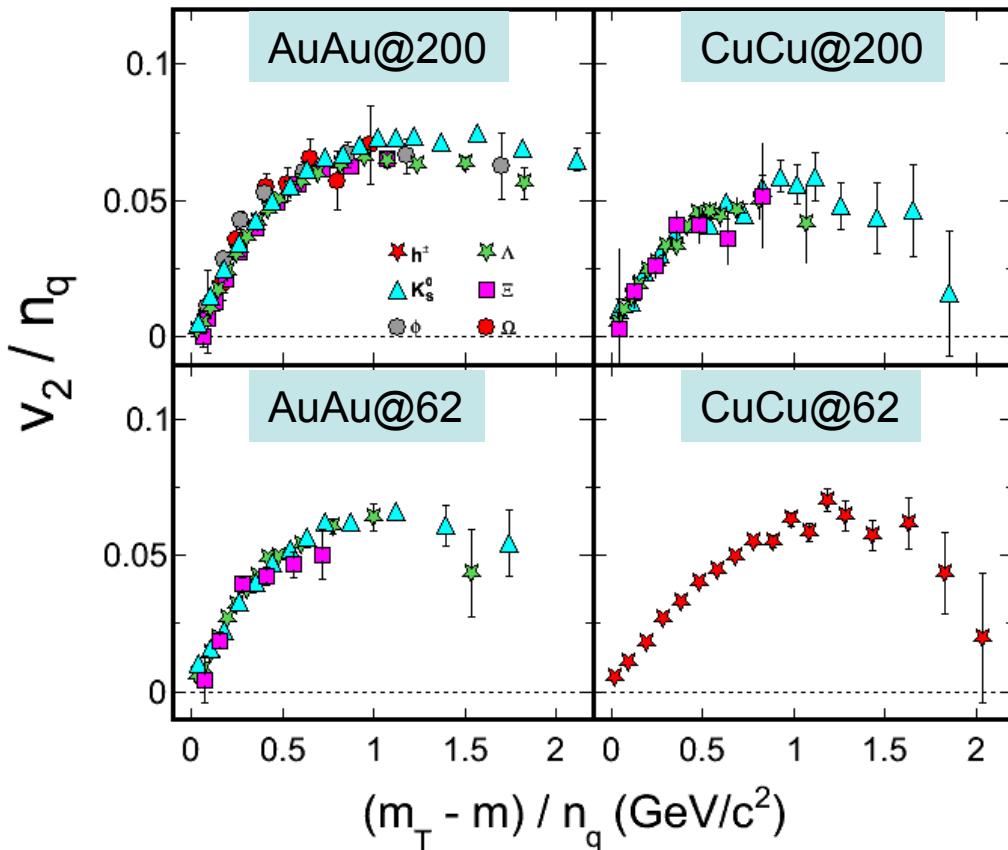
Partonic Collectivity at RHIC



PHENIX π and p : nucl-ex/0604011v1

- Low p_T ($\leq 2 \text{ GeV}/c$): mass ordering
 - High p_T ($> 2 \text{ GeV}/c$): number of quarks ordering
- Collectivity developed at partonic stage!***

Number of Constituent Quark Scaling



Au+Au and Cu+Cu

- Minimum bias events
- 200 and 62.4 GeV

Event plane

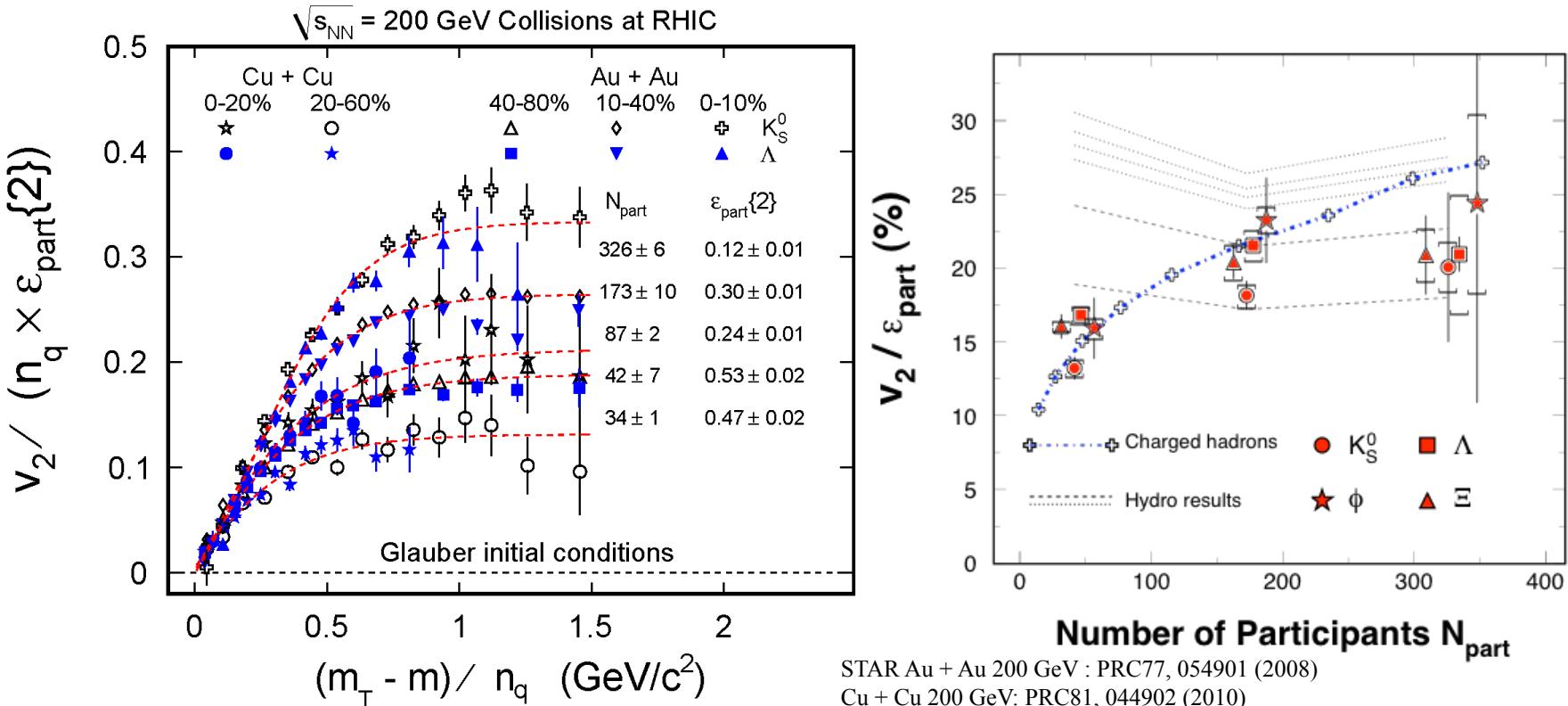
- Au+Au: TPC
Systematic: $v_2\{\text{LYZ}\}$, 10%
- Cu+Cu: FTPC
Systematic: $v_2\{\text{AA-pp}\}$, 5%

NCQ scaling

- Partonic collectivity

STAR Au + Au 62.4 GeV : PRC75, 054906 (2007)
Cu+Cu: PRC81, 044902 (2010)

Centrality Dependence

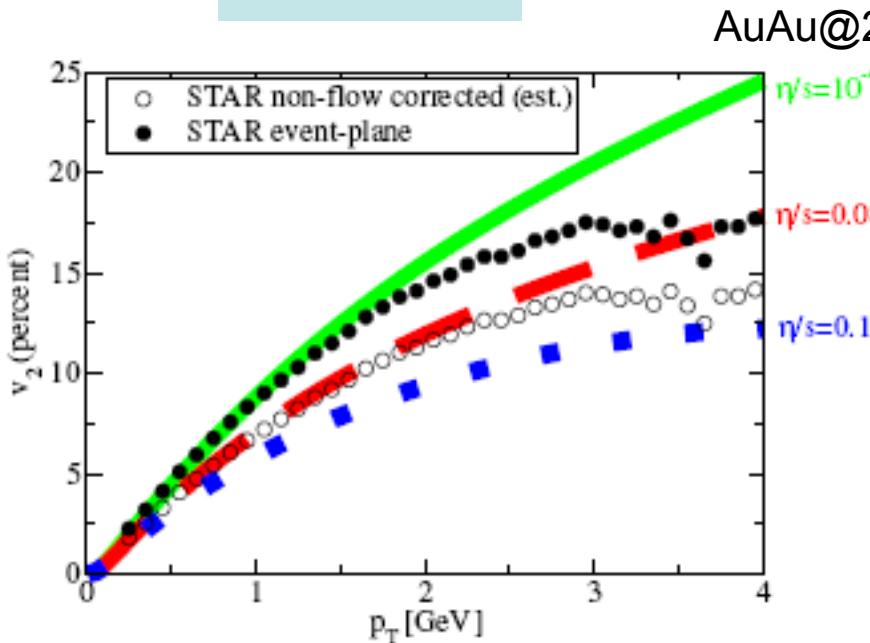


- Au+Au and Cu+Cu at 200 GeV
 - NCQ scaling for each centrality bin
- Collective flow: depends on the number of participants
 - Larger $v_2/\varepsilon_{\text{part}}$ indicates stronger collective flow in more central collisions.
 - Hint: the system created in collisions at RHIC is not fully thermalized?**
 - ➔ How about the most central Au+Au collisions?

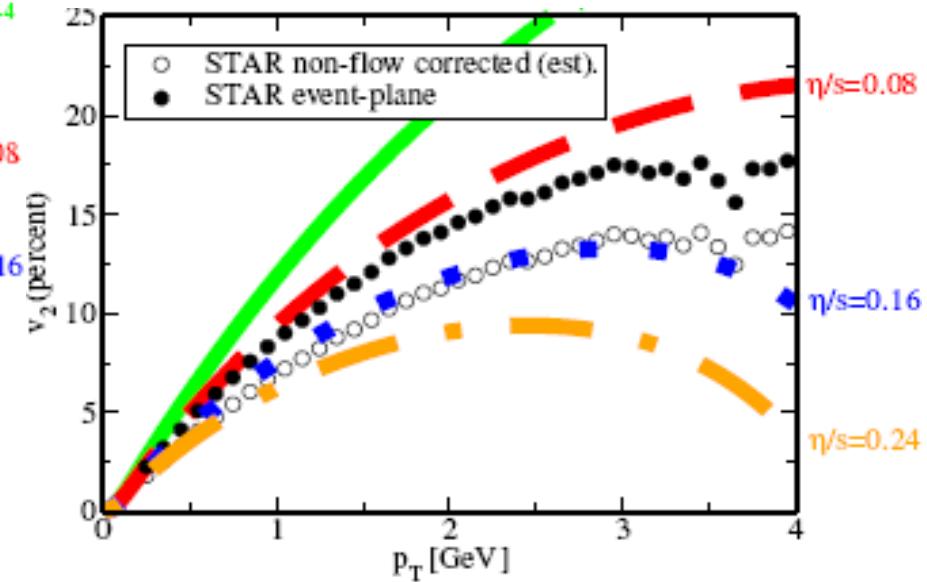
S. Voloshin, A. Poskanzer, PL B474, 27(00).
D. Teaney, et. al., nucl-th/0110037

Comparison to Viscous Hydro

Glauber



CGC

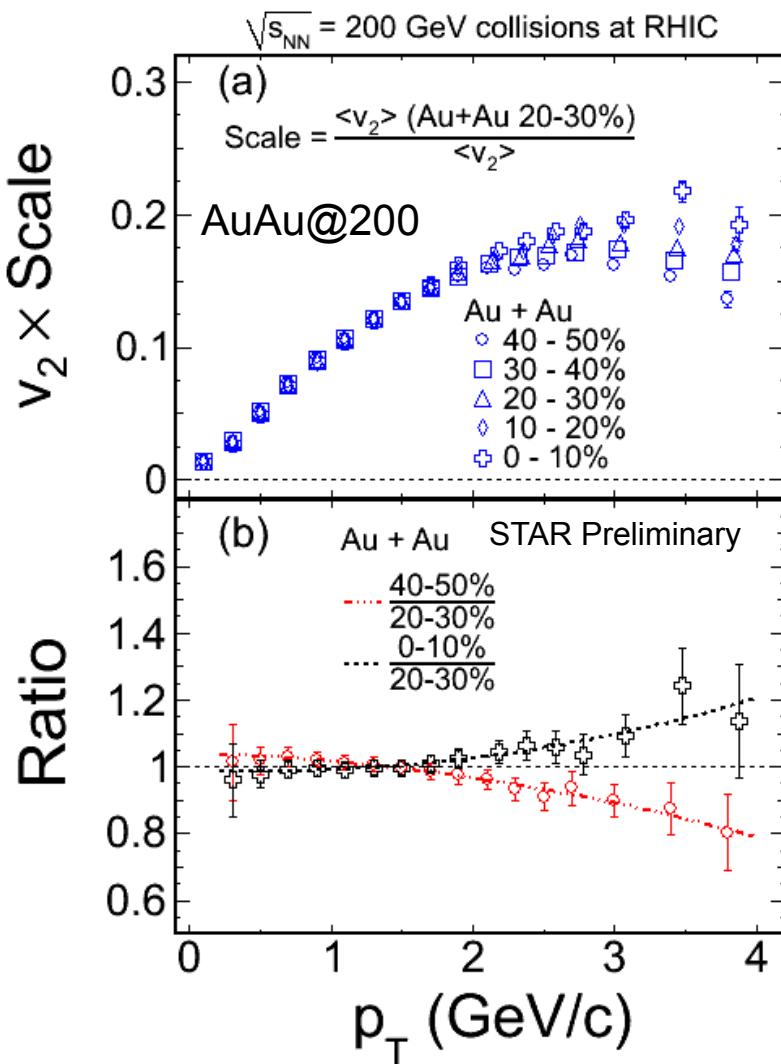


[1]P. Romatschke and U. Romatschke, Phys.Rev.Lett.99:172301, 2007 (arXiv:0706.1522)

[2]M. Luzum and P. Romatschke, Phys. Rev. C 78, 034915, 2008 (arXiv:0804.4015)

- Glauber vs.CGC ~ **a factor of 2 difference** on the extracted value of η/s
 - ➔ Strongly depends on the initial eccentricity model.

Compare the Shape of $v_2(p_T)$

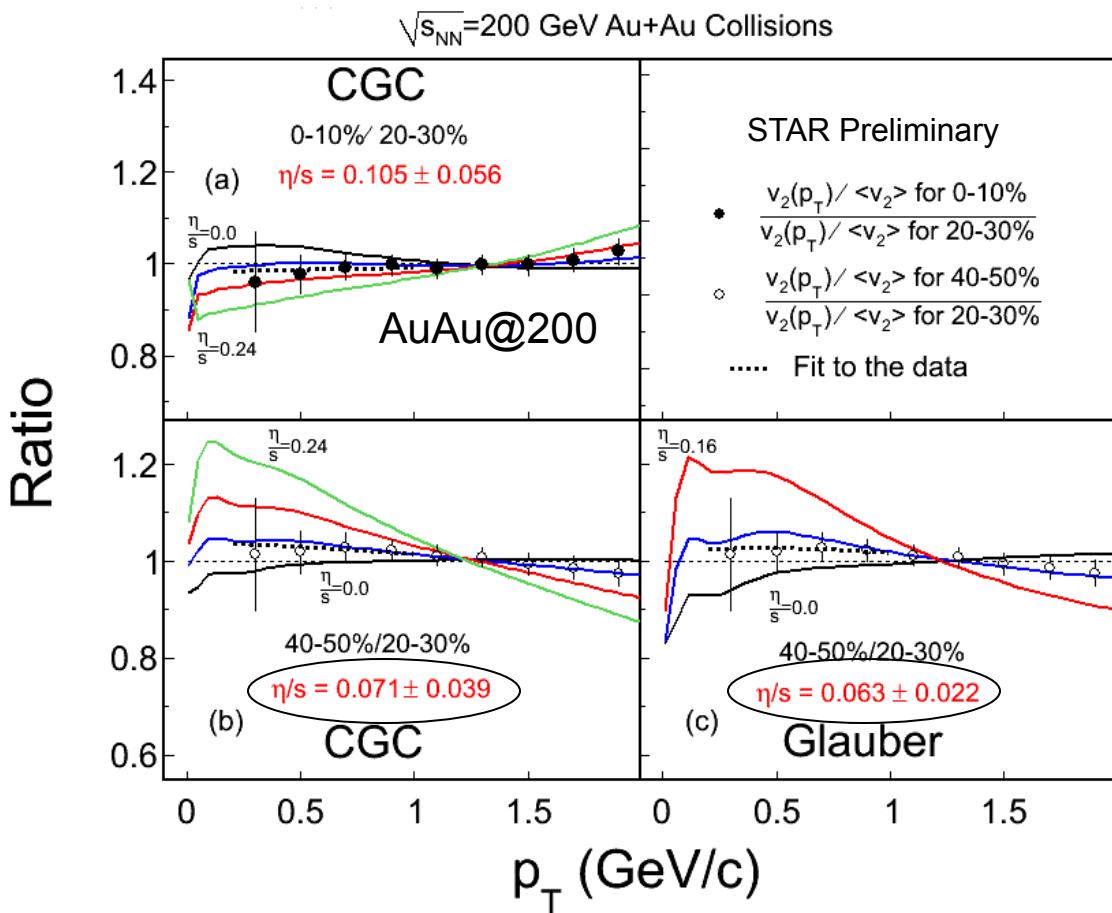


Assuming no change in viscosity at different centrality:

- (a) Normalize $v_2(p_T)$ in each centrality by the average v_2
- (b) The ratio of data points:
 - 40-50%/20-30%
 - 0-10%/20-30%

Data: $v_2\{\text{FTPC}\}$ charged hadrons

Extract η/s

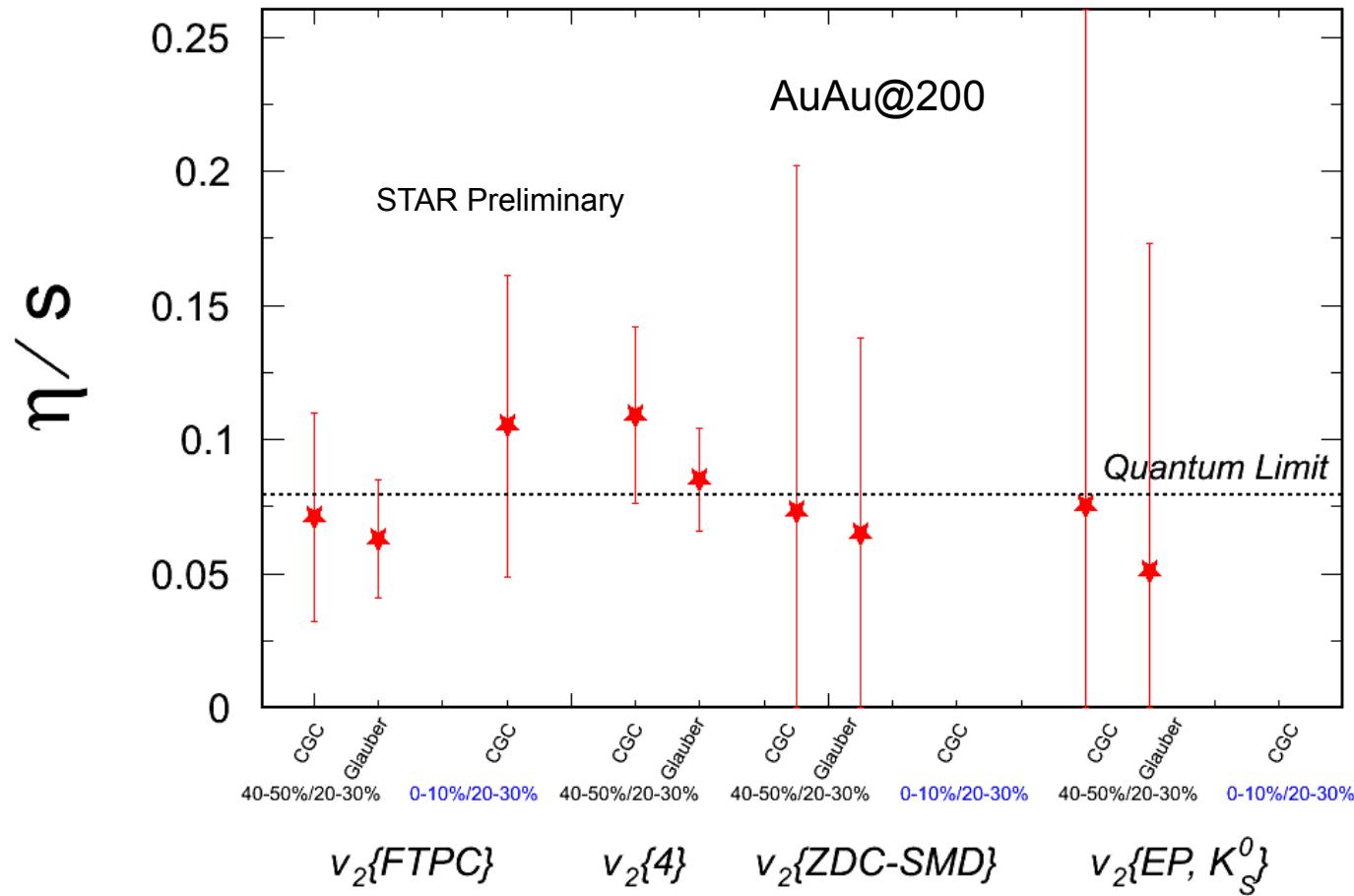


- Data: $v_2\{\text{FTPC}\}$
- Fit range:
 $0.15 < p_T < 1 \text{ GeV/c}$
- Less dependence on
the initial eccentricity
model

Assumption: η/s does not depend on the centrality.

K. Dusling, G. Moore and D. Teaney, arXiv:0909.0754

Results of Comparison to Hydro



- Less dependence on the initial eccentricity model
- $\eta/s: (0.5\sim 2)/(4\pi)$

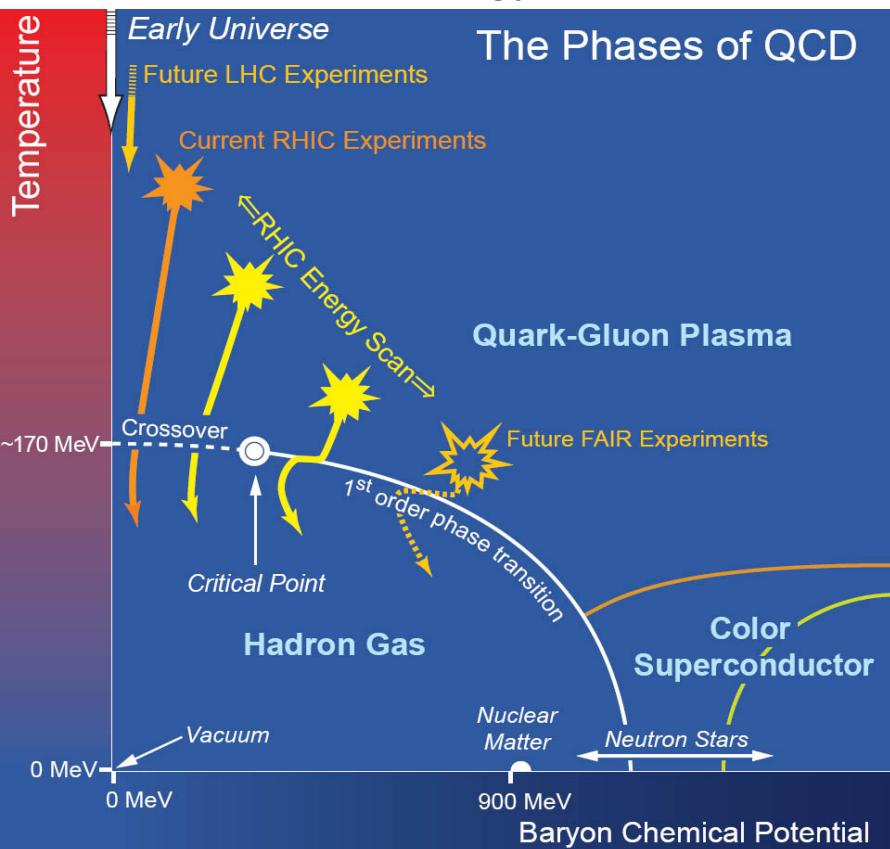
Summary I

Top Energy Collisions

- **The v_2 measurements: non-flow effect checked:**
Different methods sensitive to different nonflow, fluctuations
- **Multi-strange hadrons v_2 of ϕ , Ω at 200 GeV:**
Partonic collectivity at RHIC!
- **The shape of $v_2(p_T)$ distributions: $\eta/s: (0.5\sim 2)/(4\pi)$**
The inferred η/s depends less on the eccentricity models

QCD Phase Diagram

The RHIC Beam Energy Scan (BES)



Data Collected in 2010: Data Collected in 2011:

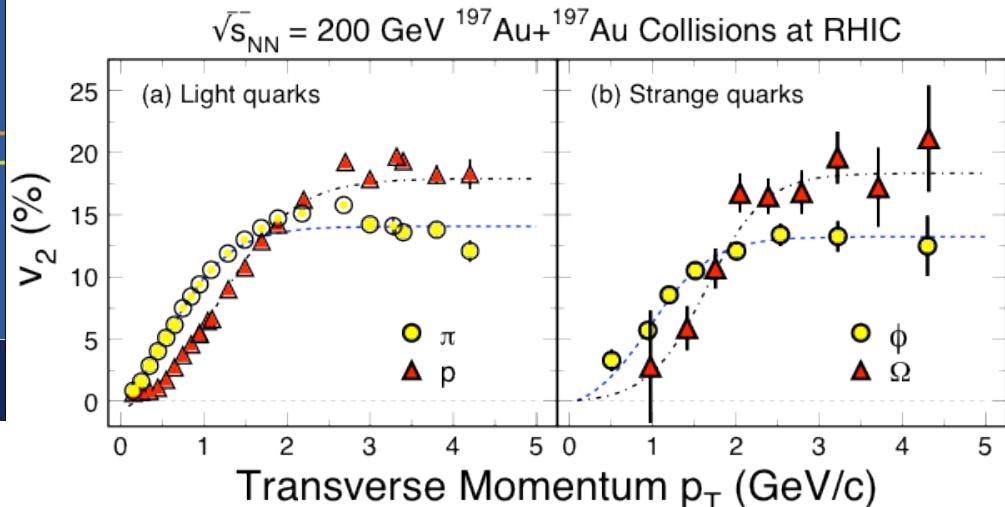
- 7.7 GeV
- 11.5 GeV
- 39 GeV
- 62.4 GeV

- 19.6 GeV
- 27 GeV

➤ BES Motivations

- Search for critical point
- Search for phase boundary

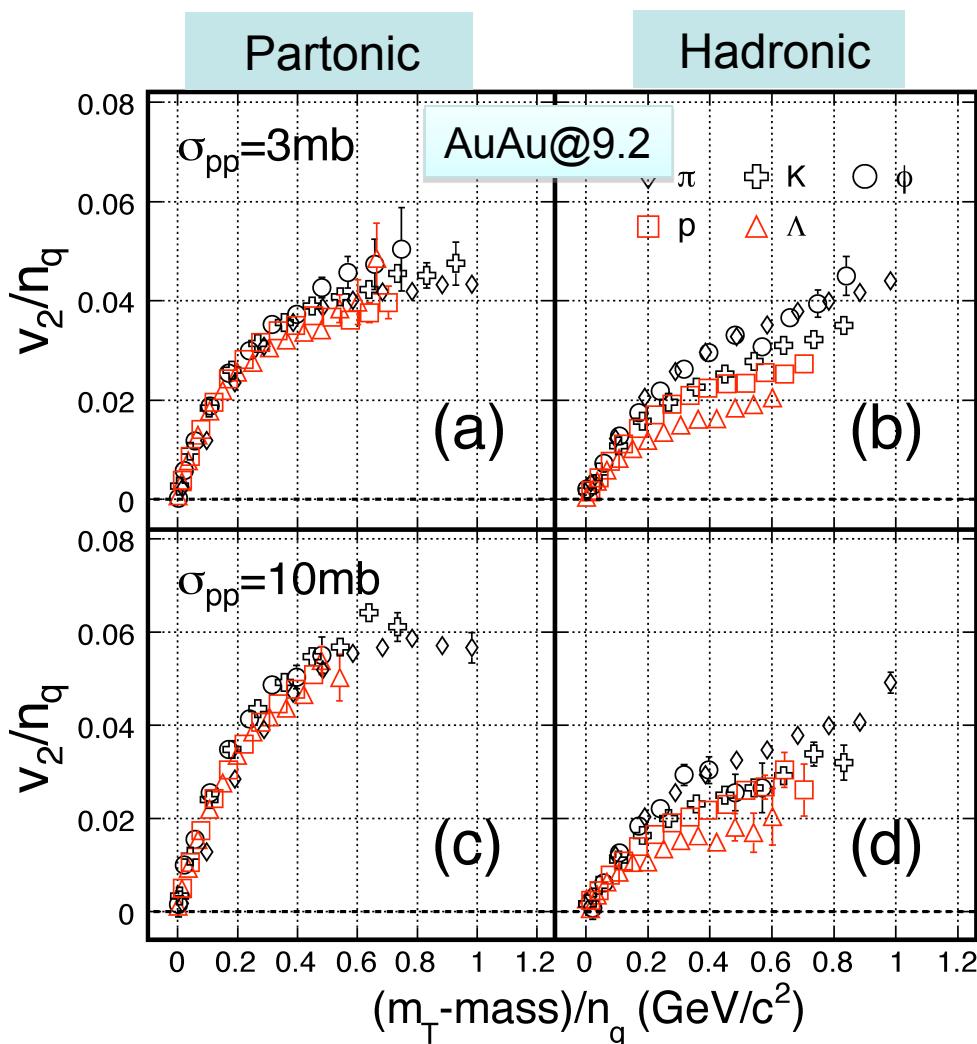
Number of Constituent Quark scaling on v_2
partonic vs. hadronic degree of freedom (dof)



STAR: PRL99, 112301 (2007)
NPA830:187c-190c(2009)
PHENIX: PRL98, 162301 (2007)

Energy Dependence of NCQ Scaling

F. Liu, K.J. Wu, and N. Xu: J. Phys. G 37 094029(2010)



AMPT model results:

- Scaling in v_2 : partonic dof dominant;
- No scaling in v_2 : hadronic dof dominant

=>

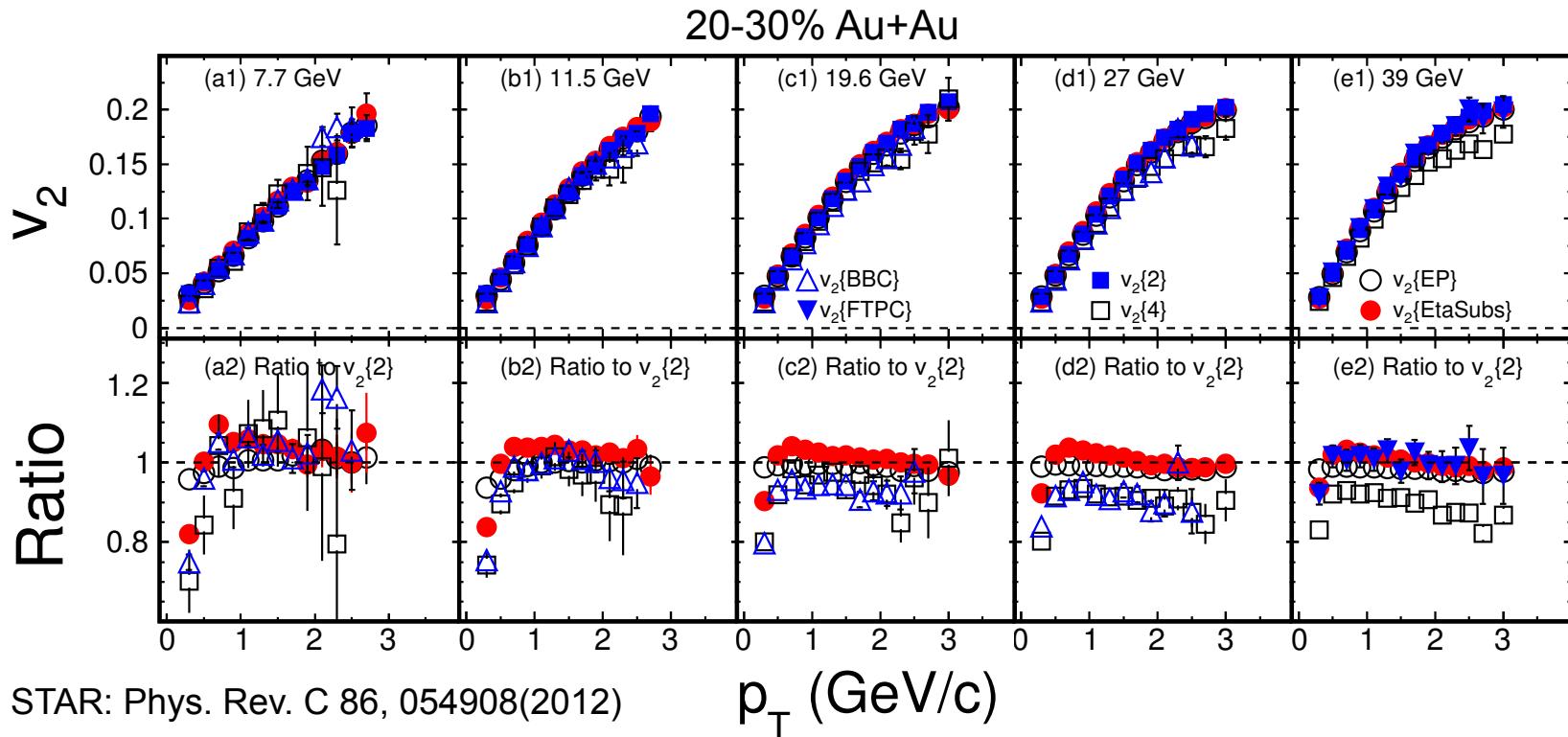
A tool to search for the possible phase boundary!

- The beam energy dependence of the partonic cross sections will not affect the v_2 scaling argument.

=>

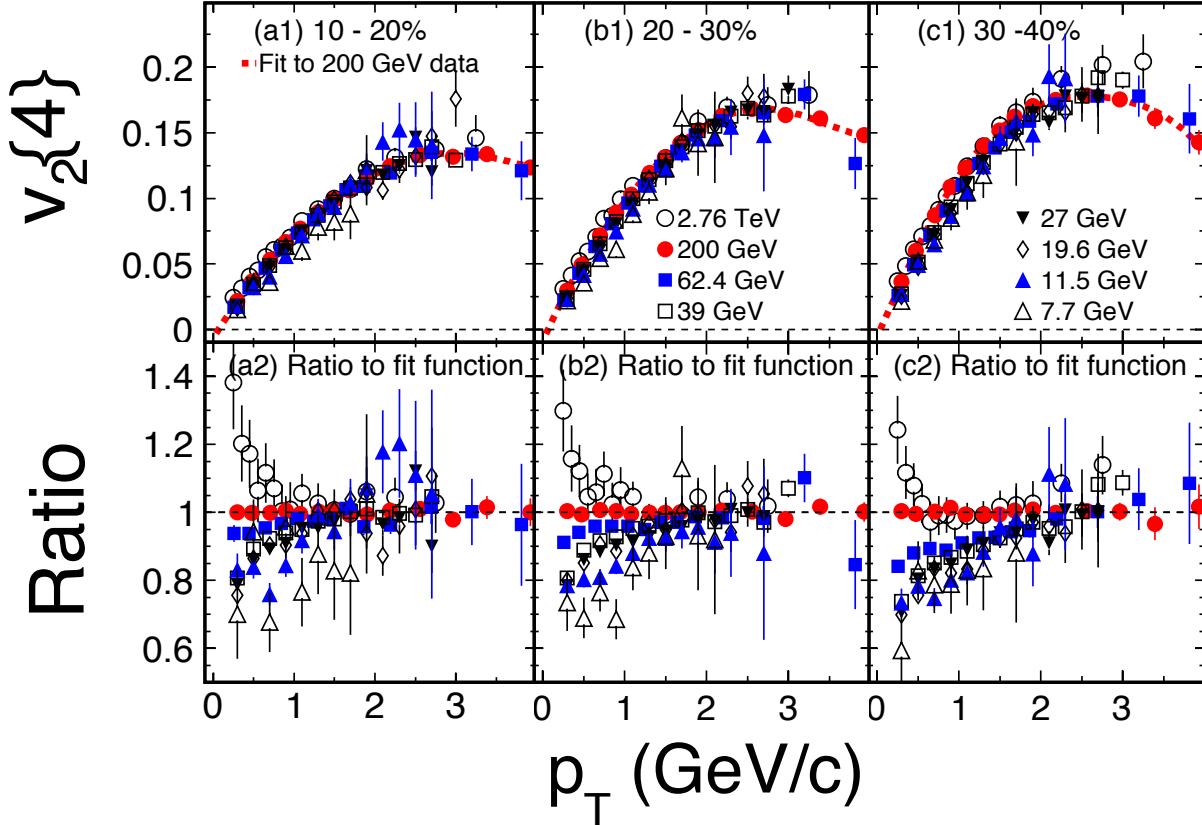
Important for Beam Energy Scan program.

Method Comparison



- **v_2 method**
 - Event Plane method TPC EP ($|\eta|<1.0$) FTPC EP ($2.5<|\eta|<4.0$) BBC EP ($3.8<|\eta|<5.2$)
 - Cumulant method $v_2\{2\}$, $v_2\{4\}$
 - Different methods show different sensitivity to non-flow and fluctuations
- **The difference between $v_2\{2\}$ and $v_2\{4\}$ decreases with decrease in beam energy**
 - non-flow and fluctuations

Energy Dependence

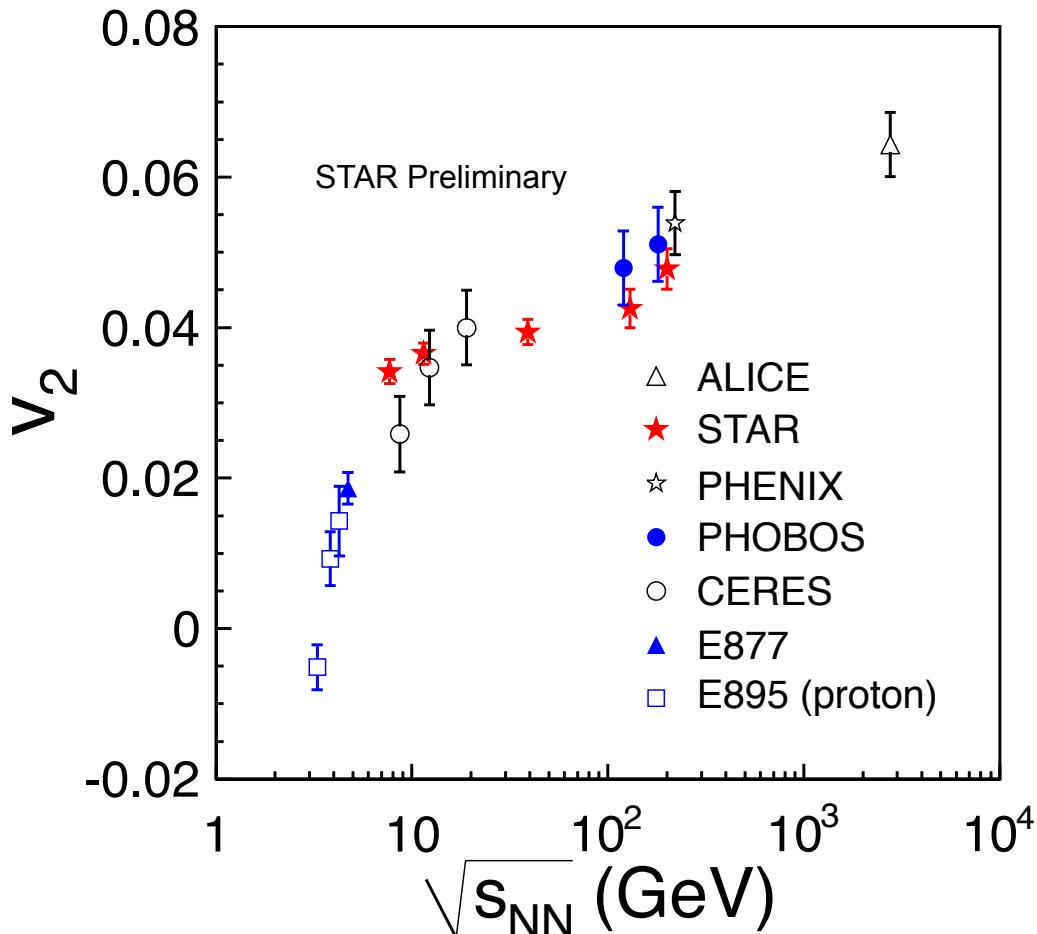


STAR: Phys. Rev. C 86, 054908(2012)

ALICE data: Phys. Rev. Lett. 105, 252302 (2010)

- **$v_2\{4\}$ results**
 - Three centrality bins
 - **Consistent $v_2(p_T)$ from 7.7 GeV to 2.76 TeV for $p_T > 2$ GeV/c**
 - **$p_T < 2$ GeV/c**
 - The v_2 values rise with increasing collision energy
- >
- Large collectivity?
Particle composition?

Energy Dependence



ALICE: Phys. Rev. Lett. 105, 252302 (2010)

PHENIX: Phys. Rev. Lett. 98, 162301 (2007).

PHOBOS: Phys. Rev. Lett. 98, 242302 (2007).

CERES: Nucl. Phys. A 698, 253c (2002).

E877: Nucl. Phys. A 638, 3c (1998).

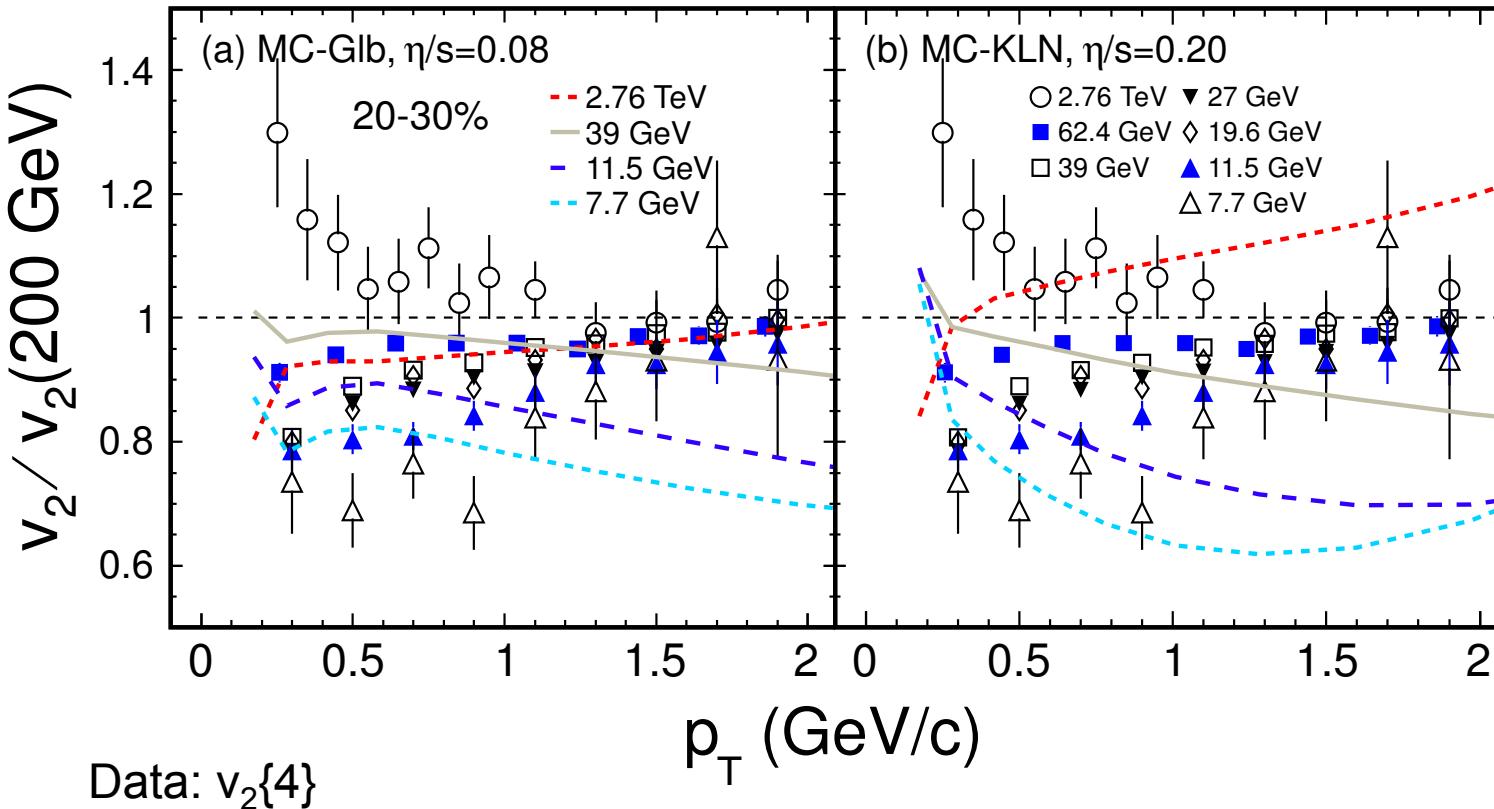
E895: Phys. Rev. Lett. 83, 1295 (1999).

STAR 130 and 200 GeV: Phys. Rev. C 66, 034904 (2002); Phys. Rev. C 72, 014904 (2005)

STAR: QM2012

- **STAR, ALICE:**
 $v_2\{4\}$ results
 - Centrality: 20-30%
- **An increasing trend is observed for p_T integrated v_2 from AGS to LHC**
 - The rate of increase with collision energy is slower from 7.7 to 39 GeV compared to that between 3 to 7.7 GeV

Comparison to Viscous Hydro

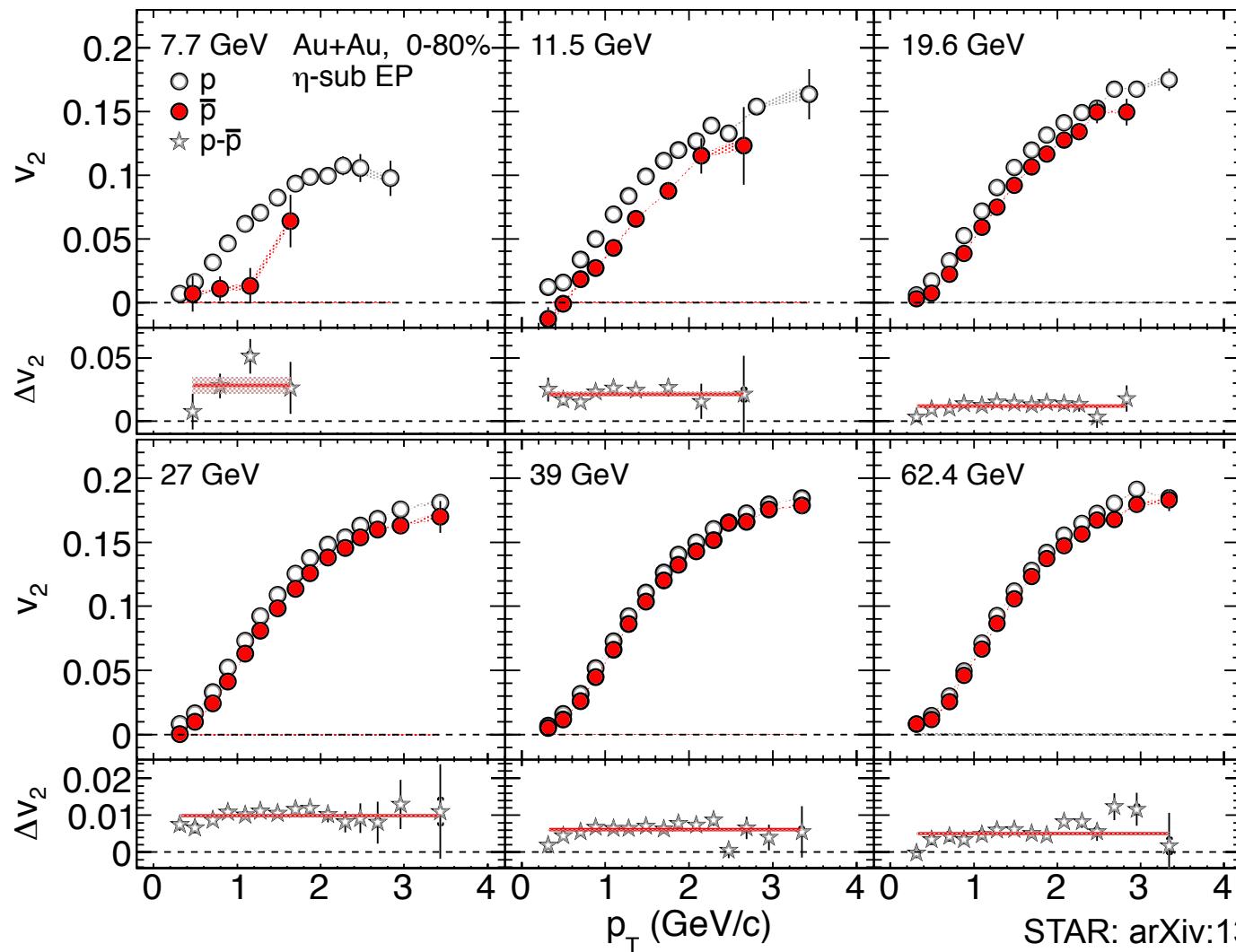


- Viscous hydro with constant η/s and zero net baryon density can not reproduce the trend of experimental data.

STAR: Phys. Rev. C 86, 054908(2012)

Hydro: C. Shen and U. Heinz, Phys. Rev. C 85, 054902(2012)

$p(\Lambda)$ vs. Anti- $p(\Lambda)$

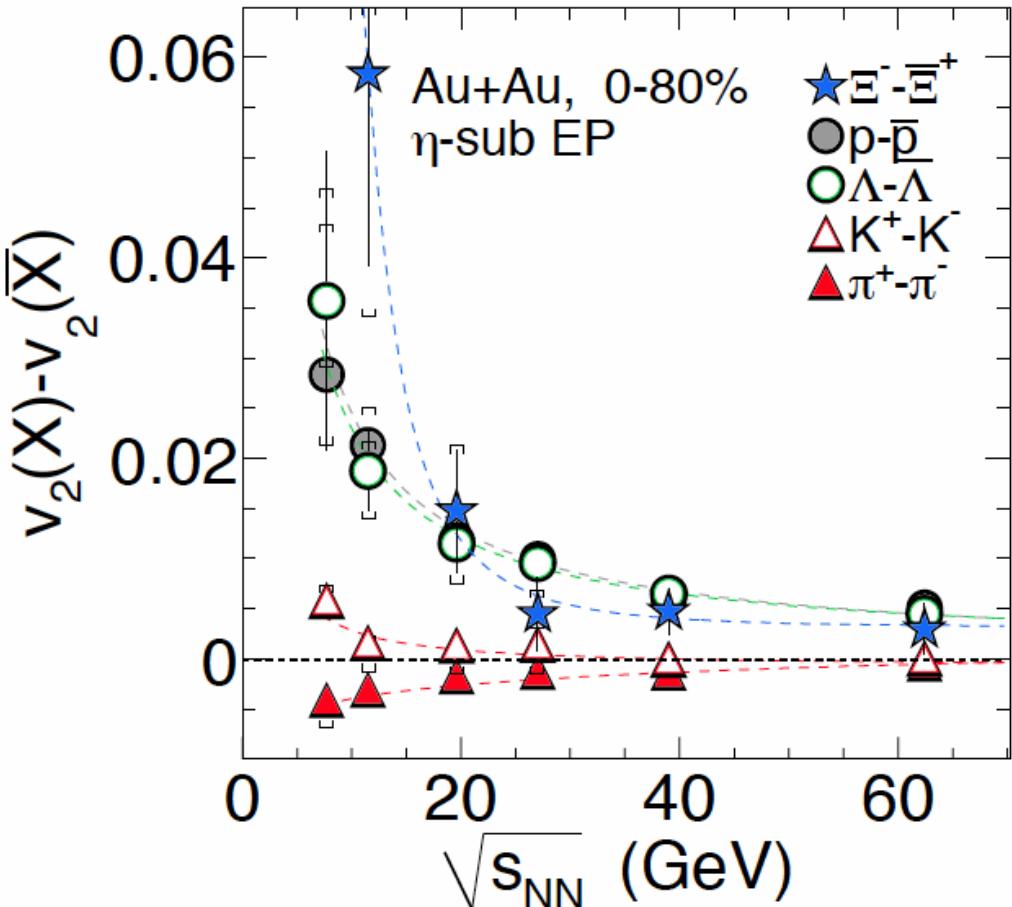


- $v_2(p) > v_2(\text{anti-}p)$ at all energies, The difference is increasing as beam energy decreasing
- Similar trend observed for Λ and anti- Λ

STAR: arXiv:1301.2347 (PRL in print),
arXiv:1301.2348

Particles vs. Anti-particles

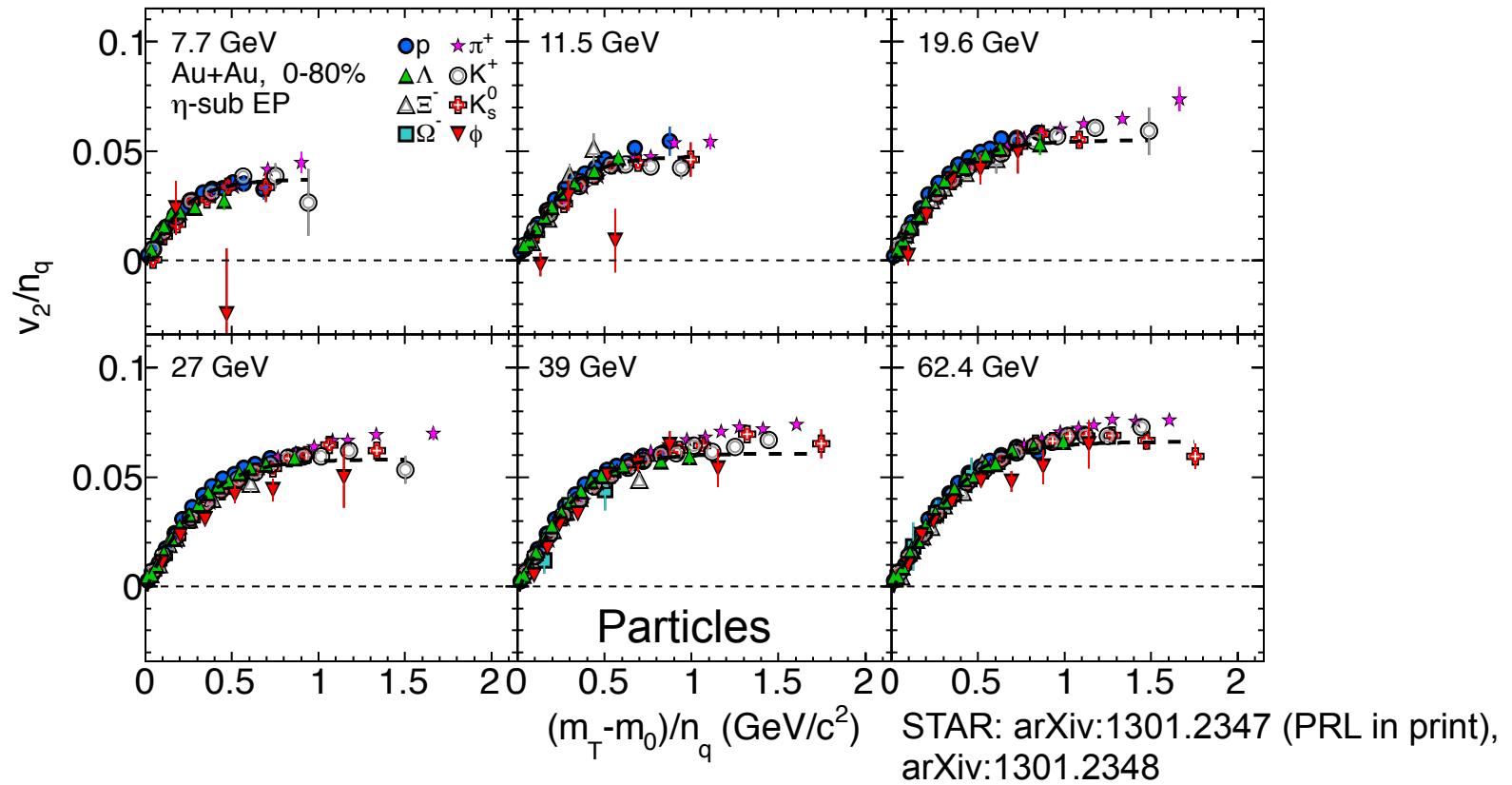
STAR: arXiv:1301.2347 (PRL in print),
arXiv:1301.2348



- **Beam energy ≥ 39 GeV**
 - Δv_2 for baryon and anti-baryon within 10%
 - Almost no difference for mesons
- **Beam energy < 39 GeV**
 - The difference of baryon and anti-baryon v_2
 - *Increasing with decrease of beam energy*
 - $v_2(K^+) > v_2(K^-)$ at 7.7-19.6 GeV
 - $v_2(\pi^-) > v_2(\pi^+)$ at 7.7-19.6 GeV
- **Possible explanation**
 - Baryon transport to mid-rapidity?
ref: J. Dunlop et al., PRC 84, 044914 (2011)
 - Hadronic potential?
ref: J. Xu et al., PRC 85, 041901 (2012)

The difference between particles and anti-particles is observed

NCQ Scaling Test



- Universal trend for most of particles and the corresponding anti-particles
- ϕ meson v_2 deviates from other particles $\sim 2\sigma$ at the highest p_T data in 7.7 and 11.5 GeV collisions

More data for 7.7 and 11.5 GeV are needed for clear conclusion

Small or zero v_2 for ϕ meson \rightarrow without formation of partonic matter

Ref: B. Mohanty and N. Xu: J. Phys. G **36**, 064022(2009)

Summary II

Beam Energy Scan

➤ Charged hadrons

Consistent $v_2\{4\}(p_T)$ from 7.7 GeV to 2.76 TeV for $p_T > 2 \text{ GeV}/c$

The p_T integrated v_2 increases as a function of collision energy more slowly between 7.7 and 39 GeV than at lower energies

➤ The difference between particles and anti-particles increases with decrease of beam energy

NCQ scaling is broken between particles and anti-particles

➤ ϕ meson deviates the trend of other particles $\sim 2\sigma$ at the highest p_T data in 7.7 and 11.5 GeV collisions

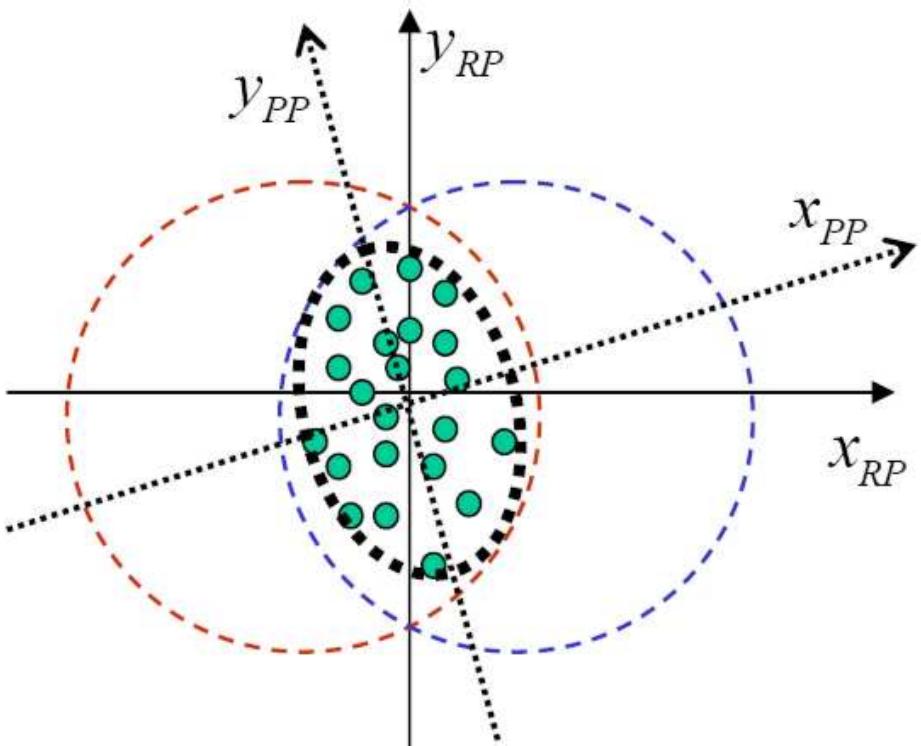
Hadronic interactions are more important at lower energies

Outlook

- The collectivity of heavy flavor: **thermalization of light flavors**
- Identify and study the property of matter (EOS) with partonic degrees of freedom
- Search for the structure of QCD phase diagram with higher precise data from BES II

backup

Participant Plane



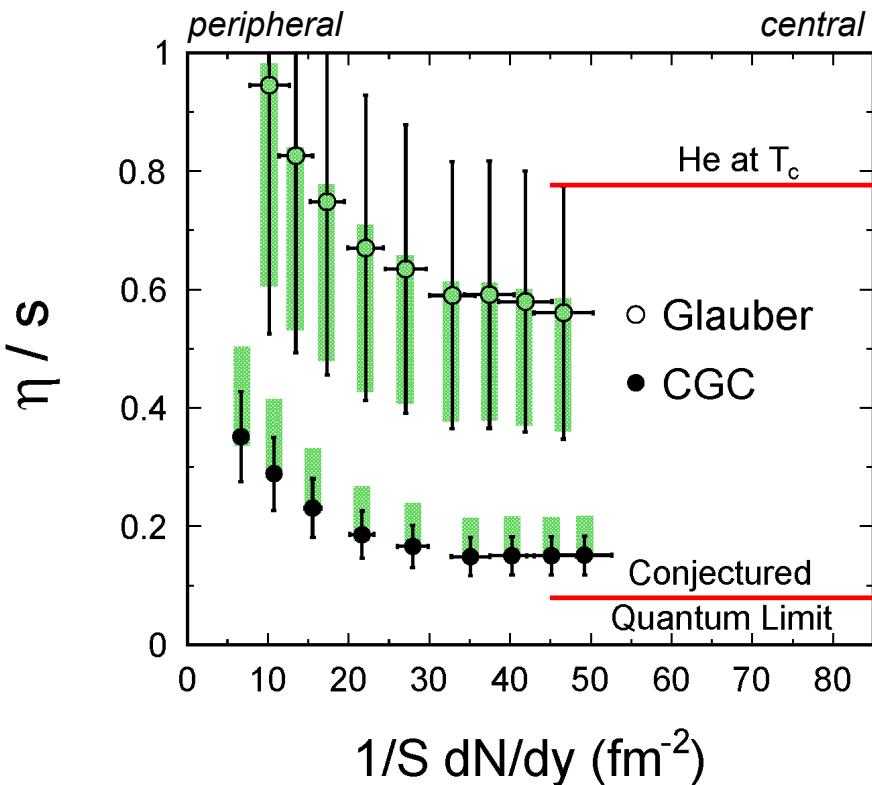
- **RP: the reaction plane**
 - Defined by the impact parameter
 - Initial geometry: ε_{std}
- **PP: the participant plane**
 - Defined by the major axis of the created system
 - Initial geometry: $\varepsilon_{\text{part}}$

PHOBOS : NPA774: 523 (2006), PRC77, 014906 (2008)

S. A. Voloshin, A. M. Poskanzer, A. Tang and G. Wang,
PLB, 659 (2008), 537-541

- v_2 from the event plane method is sensitive to the participant plane

Effective η/s



D. Teaney, PRC**68**, 034913 (2003)
 H.-J. Drescher, A. Dumitru, C. Gombeaud,
 J.-Y. Ollitrault, PRC**76**, 024905 (2007)

m_T spectra
 STAR: PRC**79**, 034909 (2009)
 PHENIX: PRC**69**, 034909 (2004)

classical ultrarelativistic gas $s = 4n$

$$\frac{\eta}{s} = 0.316 \frac{T}{\sigma n} = 0.316 \lambda T$$

$$\lambda = \frac{1}{n\sigma} = \frac{SR}{\sigma c_s} \left(\frac{dN}{dy} \right)^{-1}$$

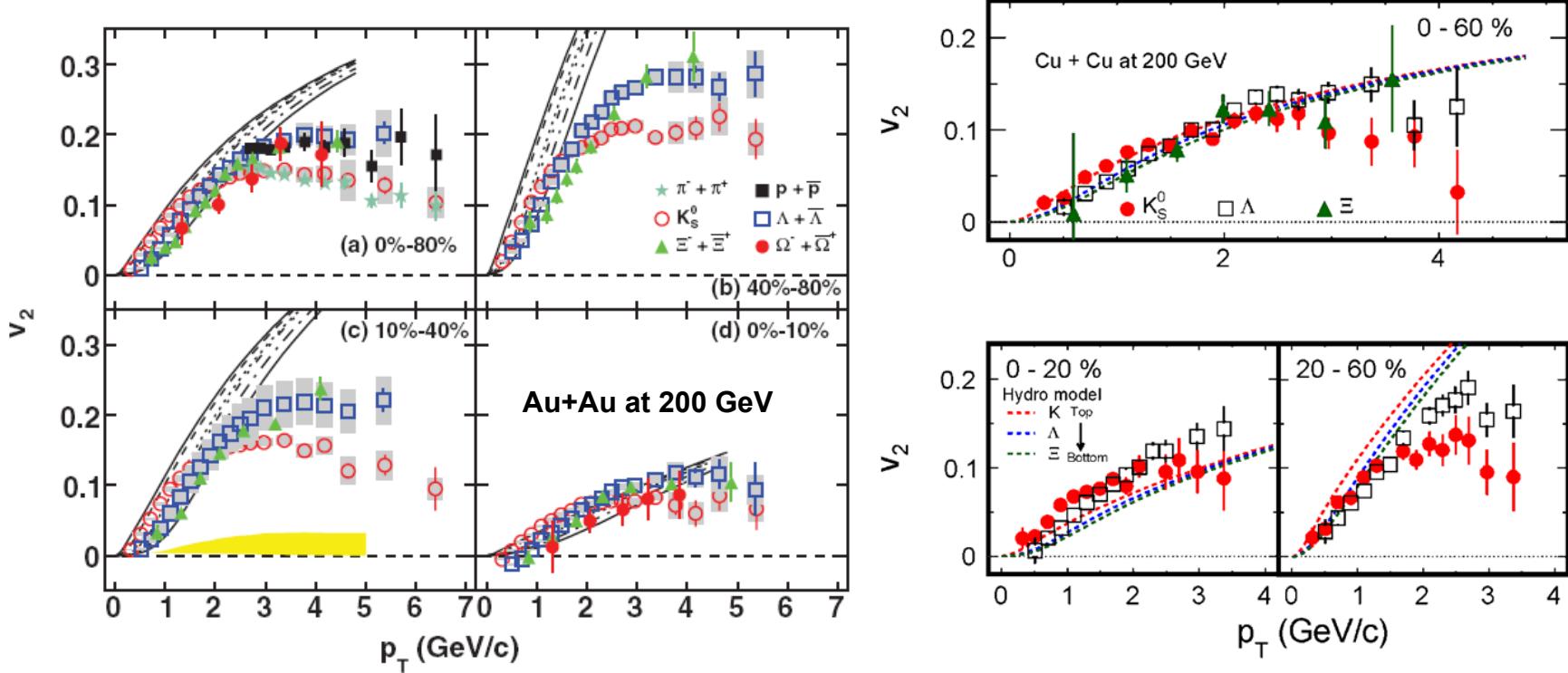
$$\frac{\eta}{s} = 0.316 T \frac{SR}{\sigma c_s} \left(\frac{dN}{dy} \right)^{-1}$$

$$T : m_T \text{ slope for } \pi, \quad \frac{1}{R^2} = \frac{1}{\langle x^2 \rangle} + \frac{1}{\langle y^2 \rangle}$$

- Effective $\eta/s \sim$ viscous hydro. Models
- Depends on the eccentricity model .
- CGC gives lower η/s , implies softer EOS.
- Caveats: No phase transition, best for dilute system of massless particles, average over all phases.

Ideal Hydro Test

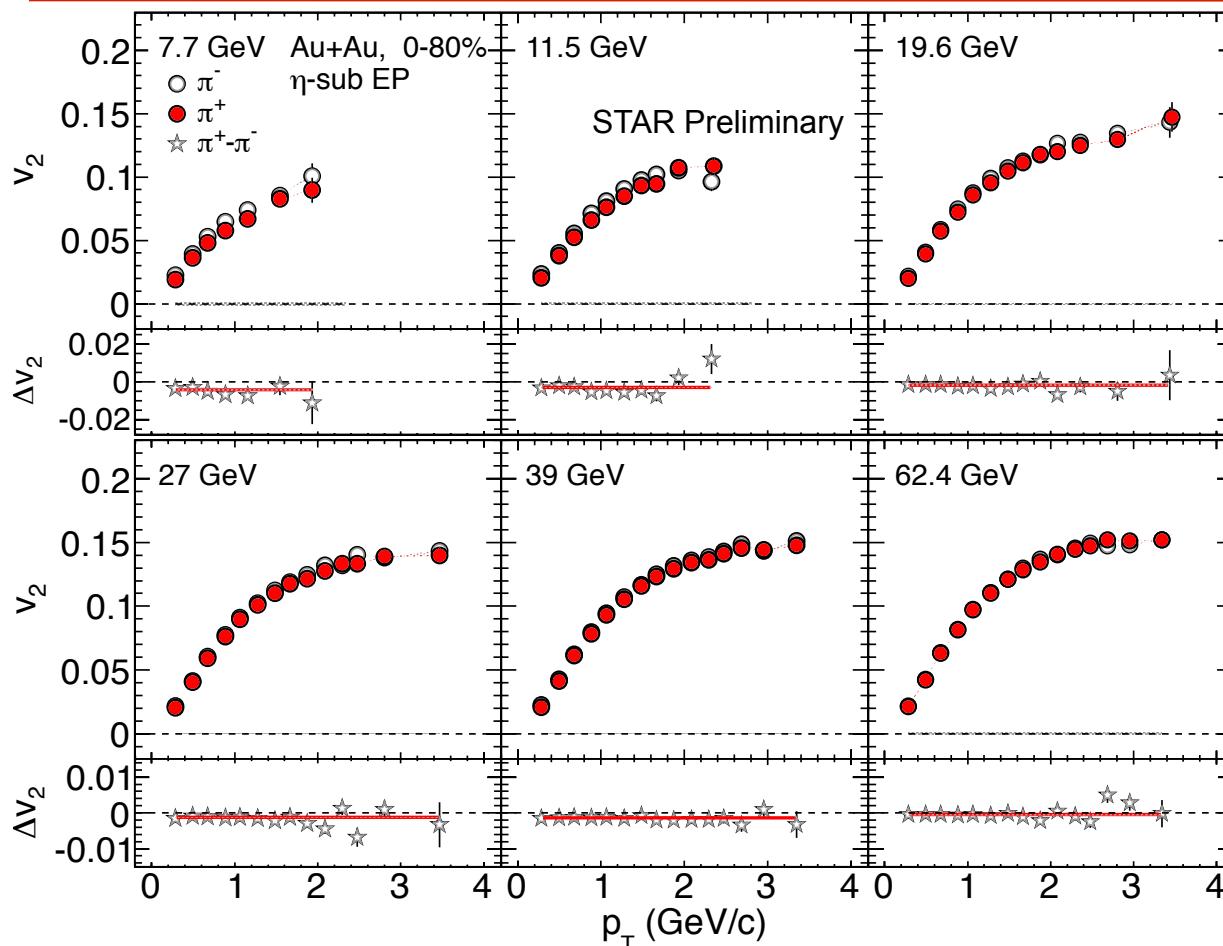
Ideal hydro: P. Huovinen, private communication



STAR Au + Au 200 GeV : PRC77, 054901 (2008)

- Ideal hydro fails to reproduce centrality dependence of the data.
Fluctuation of v_2 ? Viscosity? Incomplete thermalization?

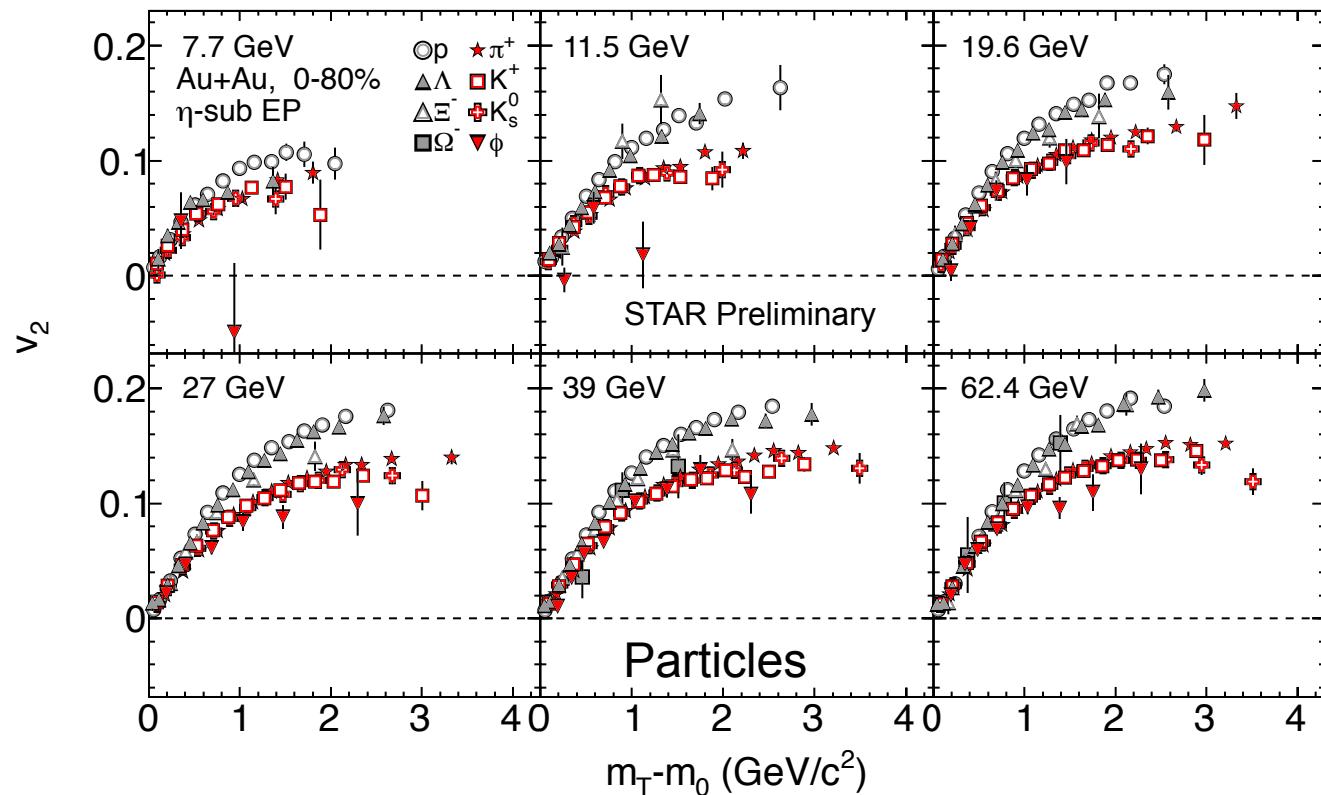
$\pi^+ (\text{K}^+) \text{ vs. } \pi^- (\text{K}^-)$



Systematic uncertainties:
 • The methods to calibrate EP
 • The parameters to determine the particle identification

- $v_2(\pi^-) > v_2(\pi^+)$ and $v_2(\text{K}^+) > v_2(\text{K}^-)$ in Au + Au collisions at 7.7 and 11.5 GeV
 - Almost same magnitude of v_2 at 19.6, 27, 39 and 62.4 GeV
- Red line: a horizontal line fit to the Δv_2 to quantify the p_T independent difference

v_2 VS. $m_T - m_0$



- Baryon–meson splitting is observed when collisions energy $\geq 19.6 \text{ GeV}$ for both particles and the corresponding anti-particles
- For anti-particles the splitting is almost gone within errors at 11.5 GeV